An Examination of Anthropogenic Climate Forcing in the 21st Century: Greenhouse Gases and Aerosols – Direct and Indirect

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with the indirect help of many
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Abstract.

The projection of future climate change – and its consequent impacts on societies and individuals – depends not only on society's direct emissions of greenhouse gases and aerosols, but also on the Earth system's response to these changes insofar as they additionally alter the radiative forcing of climate. These *feedbacks* involve coupling across the physical climate and biogeochemical systems, and they are often also designated *indirect effects*. This report examines some of the more well identified and quantified indirect effects related to atmospheric composition, as well as those that, although identified, remain highly uncertain. Although the unpredictability of anthropogenic emissions of greenhouse agents over the 21st century dominates the uncertainty of future climate, these feedbacks are a major contribution; and the big question is how such global feedbacks could be detected and quantified. The detection of feedbacks, even from an integrated Earth observing system, is a major challenge. This report is based in large part on results from the IPCC/TAR and immediate follow-on studies, and this rapporteur thanks the many lead and contributing authors to the TAR.

1. Introduction - Radiative Forcing

Many gases and aerosols in the atmosphere interact with solar and/or terrestrial radiation and thus alter the radiative balance of the Earth's climate system. The gases are often called greenhouse gases (e.g., water vapor, carbon dioxide, methane, nitrous oxide, ozone, ...), and increases lead in general to a warming of the surface. The aerosols are also recognized as greenhouse agents, either cooling (e.g., sulfate aerosols) or warming (e.g., soot). Human activities have clearly altered the atmospheric abundance of many of these greenhouse agents since the pre-industrial era (circa 1750). We alter some by direct emissions of the agents themselves (e.g., the gases CO_2, CH_4, N_2O, and CFCs, and the aerosol soot) and some through the emissions of precursors that through atmospheric chemistry impact the greenhouse agents (e.g., emissions of SO_2 are oxidized to form sulfate aerosol , or emissions of NO make O_3 but destroy CH_4). Aerosols have further indirect effects on the climate through their alteration of clouds. Water vapor, an important greenhouse gas, is predominantly determined in the troposphere by climate rather than anthropogenic emissions, but in the stratosphere CH_4 and H_2 contribute to its abundance. The largest greenhouse-gas contributions to the overall, human-driven rise in radiative forcing since 1750 are 1.46 W m^{-2} from CO_2, 0.48 W m^{-2} from CH_4, 0.35 Wm^{-2} from O_3 and 0.15 W m^{-2} from N_2O. Figure 1 summarizes the contributions to the change in radiative forcing (RF) from year 1750 to 2000 as published in the 2001 Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report (TAR). This figure is equivalent to that published (Ramaswamy, 2001) but gives a different perspective in terms of (i) the balance of CO_2 vs. the other well mixed greenhouse gases and (ii) the difference between the globally distributed forcings and those which are more locally distributed near Northern Hemisphere continents. In terms of indirect effects, the RF from CO_2 is impacted by land-use change and deforestation in addition to direct fossil fuel emissions (Prentice, 2001); the RFs from CH_4 and O_3 are affected by feedbacks within atmospheric chemistry (Prather and Ehhalt, 2001); and the several indirect effects from aerosols through impacts on clouds and the water cycle appear to be much greater than their direct RF (Penner, 2001).

Questions remain about the usefulness of the radiative forcing values (i.e., the instantaneous net radiative imbalance due to a perturbation, measured in W m^{-2} at the top of the atmosphere, after the stratospheric

temperature has adjusted), and more specifically whether the equivalent radiative forcing values from two different types of perturbations (e.g., CO_2 and tropospheric O_3, see Prather and Sausen, 1999). This has been discussed extensively in the IPCC assessment reports and the TAR concludes that it is still a useful measure of global climate change (Ramaswamy, 2001): "Radiative forcing continues to be a useful tool to estimate, to a first order, the relative climate impacts (viz., relative global mean surface temperature responses) due to radiatively induced perturbations. The practical appeal of the radiative forcing concept is due, in the main, to the assumption that there exists a general relationship between the global mean forcing and the global mean equilibrium surface temperature response ... which is similar for all the different types of forcings."

The RF bar chart in Figure 1, an expected IPCC product, has not typically been shown for future years, and so we present an equivalent chart for the year 2100 following SRES emissions scenario A2 in Figure 2. The values are taken from Appendix II of the TAR and plotted in parallel with Figure 1. Values for solar, mineral dust, aerosol indirect effects, and land-use change (albedo) were not projected and are left at their year 2000 values. The most startling feature is the dominance of CO_2. Nevertheless, the contributions from CH_4, tropospheric O_3, and aerosols is still substantial; and thus the importance of indirect effects persists into the 21st century. Further, more extensive climate change and related anthropogenic changes (e.g. nitrate deposition, desertification, land use) are expected during the 21st century as compared with the 20th century, and these are likely to lead to larger feedbacks affecting trace gases and aerosols.

2. Chemical Feedbacks

Perhaps the most important recognition over the past decade is that atmospheric chemistry is fully coupled on a global scale and that pollution on regional scales has a direct link to the global CH_4 abundance. The IPCC Second Assessment Report (1996) already recognized that CH_4 emissions affected its own lifetime and hence the effective residence time for CH_4 was 40% longer than its chemical loss lifetime. The TAR expanded the recognition of the importance of these chemical feedbacks by bringing CO into the UN FCCC policy debate on greenhouse gases: "CO is identified as an important indirect greenhouse gas. An addition of CO to the atmosphere perturbs the OH-CH_4-O_3 chemistry. Model calculations indicate that the emission of 100 Mtons of CO stimulates an atmospheric chemistry perturbation that is equivalent to direct emission of about 5 Mt of CH_4." This is based on recent global 3-D model studies of the impact of CO emissions (Wild and Prather, 2000; Derwent et al., 2001), and a sample case is shown in Figure 3. Derwent has continued these studies and expanded upon the TAR's suggestion that molecular hydrogen (H_2) is also an indirect greenhouse gas: "H_2 is not a direct greenhouse gas. But it can reduce OH and thus indirectly increase CH_4 and HFCs. . . . Currently the impact of H_2 on tropospheric OH is small, comparable to some of the VOC. No scenarios for changing H_2 emissions are considered here; however, in a possible fuel-cell economy, future emissions may need to be considered as a potential climate perturbation."

3. Other Feedbacks with the Climate System

Several possible major feedbacks involving climate change and greenhouse gases were identified in the TAR but have not yet been fully evaluated. For CO_2, the obvious concern involves changes in the land and ocean sinks. Also, warming increases the rate of heterotrophic respiration on land, and it plus regional changes in precipitation patterns and cloudiness, may alter terrestrial ecosystem structure, geographic distribution and primary production. When climate change feedbacks are included, land uptake is reduced in all models relative to CO_2 increases without climate change (Prentice, 2001). Interactive carbon-climate models are being actively used to investigate feedbacks and climate sensitivity (Jones et al., 2003; Gerber et al., 2003).

Aerosol indirect effects remain at the top of the debate on climate sensitivity (e.g., Rotstayn and Penner, 2001) as can be readily seen in the lack of a recommendation for the indirect RF and the inclusion of only *one* of the aerosol indirect effects in Figure 1.

The indirect effects of what used to be considered just regional air pollution (NOx, CO, VOC) are seen to play an important role in controlling the CH_4 abundance as well as tropospheric O_3 (Wigley et al., 2002). The change in the CH_4 sink is shown in Figure 4 for the SRES scenarios analyzed in the TAR. Moreover, these changes include only the direct effect

of anthropogenic emissions and do not include the effects fo climate change. Recently, Johnson et al (2001) point out the much warmer, wetter world predicted under SRES A2 dramatically reduces tropospheric O_3 abundances.

The recently recognized link of climate forcing with local air quality, has global scale pollution building up background levels of ozone and threatening local attainment of air quality standards (Prather et al., 2003), while recognizing that regional pollution is responsible for much of the tropospheric ozone and black carbon that contributes to global warming (Hansen, 2002).

4. Detection and Quantification of Feedbacks

Verifying these model-derived feedback mechanisms from observations of the Earth system will be very difficult. For example, one might think that the CH_4 feedback effect on its own lifetime would be detectable, but this would require a highly precise knowledge of the absolute emissions of CH_4, both natural and anthropogenic over several years. The inherent nature of feedbacks among the biogeochemical and physical climate systems makes their detection almost impossible since we cannot run "experiments" with the system and know enough of the controls (e.g., natural emissions). The best hope lies with the global integration possible from combined satellite and surface/suborbital measurements. For example, it may be possible to identify a pattern of coupled perturbations to CH_4-CO-O_3 that match those predicted in the models and thus would support the calculated feedbacks.

References

Derwent, R.G., et al, Transient Behaviour of Tropospheric Ozone Precursors in a Global 3-D CTM and their Indirect Greenhouse Effects, Climatic Change 49: 463-487, 2001.

S. Gerber et al., Constraining temperature variations over the last millennium by comparing simulated and observed atmospheric CO_2, Climate Dynamics 20: 281–299, 2003.

Hansen, J.E., ed., Air Pollution as a Climate Forcing: A Workshop, Honolulu, Hawaii, 29 Apr - 3 May 2002.

Johnson, C. E., D. S. Stevenson, W. J. Collins, and R. G. Derwent, Role of climate feedback on methane and ozone studied with a coupled ocean-atmosphere-chemistry model. Geophys. Res. Lett., 28, 1723-1726, 2001.

Jones, C.D. et al., Strong carbon cycle feedbacks in a climate model with interactive CO2 and sulphate aerosols, Geophys. Res. Lett., 30(9), 1479, doi:10.1029/2003GL016867, 2003.

Penner, J. E., Chapter 5. Aerosols, their Direct and Indirect Effects, in Climate Change 2001: The Scientific Basis , pp. 289-348, Houghton, J.T., et al. (eds), Cambridge U. Press, Cambridge, 2001.

Prather, M., R. Sausen, et al., Chapter 6, Potential Climate Change from Aviation, in Aviation and the Global Atmosphere, eds. J.E. Penner et al., Cambridge U. Press, pp.185-215, 1999.

Prather, M. and D. Ehhalt, Chapter 4. Atmospheric Chemistry and Greenhouse Gases, in Climate Change 2001: The Scientific Basis , pp. 239-287, Houghton, J.T., et al. (eds), Cambridge U. Press, Cambridge, 2001.

Prather, M. et al., Fresh air in the 21st Century?, Geophys. Res. Lett., 30(2),1100, doi:10.1029/2002GL016285, 2003.

Prentice, I.C., Chapter 3, The Carbon Cycle and Atmospheric Carbon Dioxide, in Climate Change 2001: The Scientific Basis , pp. 183-238, Houghton, J.T., et al. (eds), Cambridge U. Press, Cambridge, 2001.

Ramaswamy, V., Chapter 6, Radiative Forcing of Climate Change, in Climate Change 2001: The Scientific Basis , pp. 349-416, Houghton, J.T., et al. (eds), Cambridge U. Press, Cambridge, 2001.

Rotstayn, L.D., Penner J.E., Indirect aerosol forcing, quasi forcing, and climate response, J. Climate, 14 (13): 2960-2975 2001.

Wigley, T. M. L., et al., Radiative forcing due to reactive gas emissions. J. Climate, 15(18), 2690–2696, 2002.

Wild, O. and M.J. Prather, Excitation of the primary tropospheric chemical mode in a global three-dimensional model, J. Geophys. Res., 105, 24647-24660, 2000.

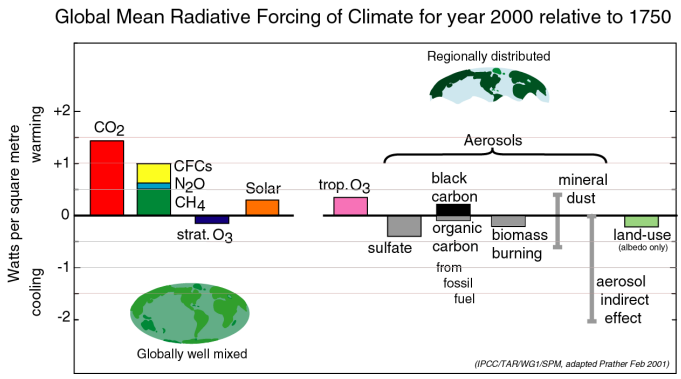

Figure 1. The Radiative Forcing due to changes in trace gases, aerosols, solar intensity, and land-use change (albedo only) from 1750 to 2000. The numbers are taken from the IPCC TAR (Ramaswamy, 2001) but have been re-plotted to compare CO_2 more directly with the other forcings and to separate global from hemispheric/regional forcings (adapted from D. Albritton).

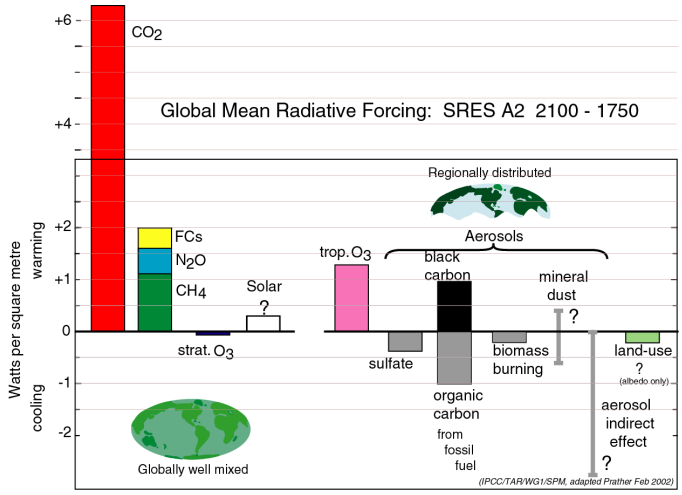

Figure 2. The Radiative Forcing due to changes in trace gases and aerosols from 1750 to 2100 following SRES scenario A2. The numbers are taken from the IPCC TAR Appendix II. Values for solar, mineral dust, aerosol indirect effects, and land-use change were not projected and are left at their year 2000 values.

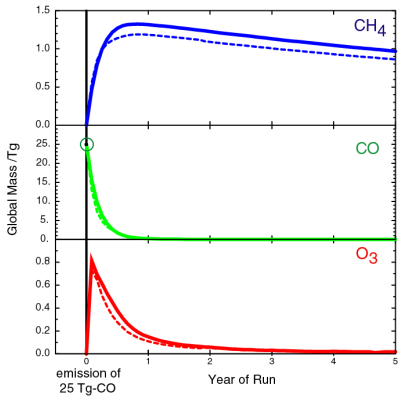

Figure 3. The response to instantaneous emissions of CO (25 Tg-CO) from European fossil fuel (dashed line) and from tropical African biomass burning (solid). Curves are the global content integrated in the 3-D model of Wild and Prather (2000). The increase in CH_4 - an indirect greenhouse effect - persists for decades after the primary pulse of CO has decayed.

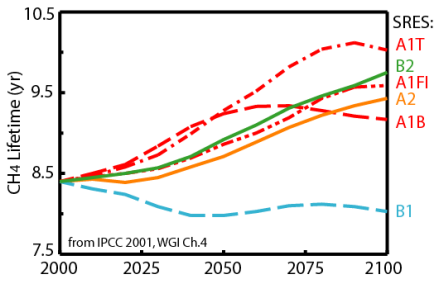

Figure 4. The atmospheric lifetime of CH_4 varies not only with the abundance of CH_4, but also with the emissions of pollutants related to local air quality (NOx, CO, VOC). The increasing lifetime for most of the SRES scenarios is an indirect effect that leads to greater residence times and hence larger impact from both natural and anthropogenic CH_4 emissions later in the century. Taken from IPCC TAR Chapter 4.